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NORTH CAROLINA STATE UNIVERSITY AT RALEIGH

SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCES

DEPARTMENT OF GEOSCIENCES
Box 5966 Zip 27607

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Investigation Title: Utilization of ERTS-A Data in Geological Evaluation, Regional Planning, Forest Management, and Water Management in North Carolina

Proposal No. 18

GSFC ID UN 281

Principal Investigator: Charles W. Welby

Charles W. Welby

Date: July 1972

The objective of the contract is to demonstrate the usefulness of ERTS-A data to various state and local agencies.

The period 1 May - 30 June has been spent acquainting the State Agencies cooperating in the investigation with the details of the program. Time has been spent also in contacting various key personnel at the federal, state and local level for their cooperation in the program. Cooperation of the North Carolina State University Agricultural Research Stations has been obtained. Discussions have been held also with the State office of the Soil Conservation Service to outline problems of mutual interest and concern.

In conjunction with the ERTS program, and supplementing it, proposals have been submitted for funding of viewers; bids are being requested for a multispectral camera whose purchase was authorized in the Spring.

During July additional contacts will be made with various federal, state and local agencies to obtain their assistance in defining particular problems to which ERTS-A data may be applicable.

At this point in time the funds appear adequate to complete the contract. The cooperating state agencies are arranging to transfer their contributions into the University's accounting system.

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DEPARTMENT OF GEOSCIENCES
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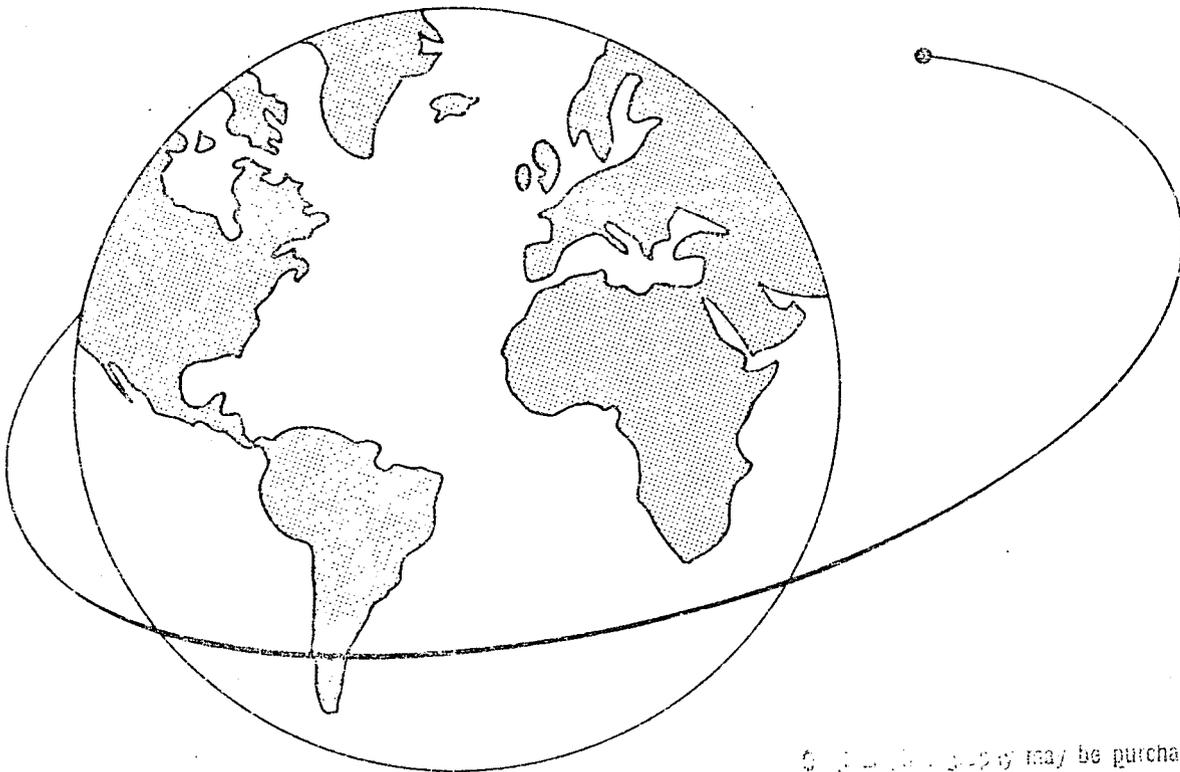
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ERTS-1 IMAGERY OF EASTERN AFRICA : A FIRST LOOK AT THE GEOLOGICAL STRUCTURE OF SELECTED AREAS

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P. A. MOHR



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**ERTS-1 IMAGERY OF EASTERN AFRICA:
A FIRST LOOK AT THE GEOLOGICAL STRUCTURE
OF SELECTED AREAS**

Paul A. Mohr

December 20, 1972

Smithsonian Institution
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II

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ABSTRACT

ERTS imagery of the African rift system resolves the major Cainozoic faults, zones of warping, and associated volcanism. It also clearly depicts the crustal "grain" of the Precambrian rocks where these are exposed.

New structural features, or new properties of known features – such as greater extent, continuity, and linearity – are revealed by the ERTS imagery. This applies, for example, to the NE–SW fracture zones in Yemen, the Aswa mylonite zone at the northern end of the Western Rift, the Nandi fault of western Kenya, the linear faults of the Elgeyo escarpment in the Gregory Rift, and the hemibasins of warped Tertiary lavas on the Red Sea margin of Yemen, matching those of the Ethiopian plateau–Afar margin.

A tentative scheme is proposed, relating the effect on the pattern of Cainozoic faulting of the degree of obliquity to Precambrian structural trend. It is particularly noteworthy that, even where the Precambrian grain determines the rift faulting to be markedly oblique to the overall trend of the rift trough – for example, in central Lake Tanganyika – the width of the trough is not significantly increased.

Some ground-mapped lithological boundaries are obscure on ERTS imagery. This is partly due to the limitations of satellite imagery, but it also seems that present approaches to mapping of Precambrian terrain in Africa may require radical revision with the input of satellite imagery.

RESUME

Les images prises par ERTS du système de cassures africaines permettent de voir les plus importantes failles du Cainozoïque, les zones de plissement et le volcanisme associé. Elles montrent aussi clairement le "grain" de la croûte des roches précambriennes, là où elles sont exposées.

De nombreux traits structuraux ou de nouvelles propriétés de traits connus, telles que plus grande étendue, continuité et linéarité, sont révélées par les images de ERTS. Ceci s'applique par exemple aux zones de la cassure NE-SO dans le Yémen, à la zone mylonite de l'Aswa à l'extrémité nord du Fossé de l'Ouest, à la faille de Nandi au Kenya de l'ouest, aux failles linéaires de l'escarpement de l'Elgeyo dans le fossé de Gregory et aux hémibassins de laves plissées du tertiaire au bord de la Mer Rouge dans le Yémen, correspondant à ceux du plateau éthiopien, au bord de l'Afar.

On suggère de relier l'effet sur la configuration de la faille du Cainozoïque du degré d'obliquité par rapport à la direction structurale précambrienne. Il est particulièrement remarquable que même là où le grain précambrien oblige la faille à être assez oblique par rapport à la direction générale du creux du fossé - par exemple au centre du lac Tanganyika - la largeur du creux ne soit pas augmentée, d'une façon appréciable.

Quelques unes des limites lithologiques établies à terre sont obscures sur les images de ERTS. Ceci est du en partie aux limitations des images par satellite, mais il semble aussi que les approches actuelles de cartographie du terrain précambrien en Afrique puissent être sujettes à une révision radicale due à l'arrivée des images par satellite.

КОНСПЕКТ

Изображения Африканской системы разломов и грабенов, переданные со спутника ERTS, дают ясную картину кайнозойских разломов и зон складчатости и связанных с ними вулканизма. На этих изображениях также можно ясно видеть коровую "текстуру" горных пород в местах их обнажений.

Изображения, полученные со спутников ERTS, позволили выявить новые структурные особенности, или, вернее, новые черты ранее известных особенностей - большее простирание, сплошность и линейность структур. Это справедливо, например, в отношении зон трещин в Йемене, простирающихся с северо-востока на юго-запад, зоны Милонитов Асва на северном краю Западного рифта, сбросовой впадины Нанди, в западной Кении, линейных сбросов Элгейского вертикального обнажения пород в зоне разломов и грабенов Грегори, и гемибассейнов третичного возраста в пограничной зоне Йемена со стороны Красного моря. Эти лавовые нагромождения сходны с образованиями на границе между плато Эфиопии и пустыней Афар.

В настоящей работе выдвигаются предварительные заключения о том, что тип кайнозойских разломов и сбросов зависит от степени их наклона относительно общего направления простирания докембрийских структур. Особенно следует отметить, что даже в тех случаях, где докембрийская текстура показывает, что сбросовые нарушения и разломы располагаются явно косо по отношению к общему направлению рифтовой синклинали (трога) например, в центральной части озера Танганьика-заметного увеличения ширины синклинали (трога) не наблюдается.

Некоторые литологические границы, имеющиеся на топографических картах, неясны на изображениях, переданных с исследовательского спутника ERTS. Частично это объясняется ограниченными возможностями получения четких снимков со спутников, но в то же время напрашивается вывод, что с получением изображений с помощью спутника потребуются радикально пересмотреть современный подход к вопросу картографирования докембрийских структур в Африке.

ERTS-1 IMAGERY OF EASTERN AFRICA:
A FIRST LOOK AT THE GEOLOGICAL STRUCTURE OF SELECTED AREAS

Paul A. Mohr

1. INTRODUCTION

Owing to the wide interest in the African rift system, and the continuing discussion over its place in the global plate-tectonic scheme, the writer proposed to NASA that imagery from the Earth Resources Technology Satellite (ERTS) be made of eastern Africa. This would make possible, for the first time, a mapping of the whole of this continental crustal-fracture system on a unified basis. The structural geology of parts of the African rift system remain poorly known from ground surveying, and thus it was hoped also to fill in some "gaps."

The proposal was approved by NASA for the ERTS-A project, and with the successful launching of ERTS-1, the first batches of multispectral scanner imagery are now becoming available. Their general excellence demands a preliminary analysis of selected areas, to bring to public notice the potential value of this imagery. In fact, the original contract was for return-beam vidicon imagery, but a problem with this system in ERTS-1 has necessitated using the alternative of multispectral scanner imagery.

The area under contract to be imaged is approximately 5 million km². This is equivalent to two-hundred 1.5 degree-square images, presuming no overlap. The detailed mapping that can be done from this large amount of imagery may well supply the mining and geological survey departments of eastern Africa with abundant work that

This work was supported in part by contract NAS 5-21748 from the National Aeronautics and Space Administration.

can continue concomitantly with the improvement of ground resolution in subsequent satellite imagery. The writer is contracted to map and study only the major rift structures revealed by ERTS-1, and it is to selected areas where imagery is already available (as of October 1972) that attention is given here. Analysis has been made from hand-lens examination of 24×24 cm prints, each covering 150×150 km on the ground, reproduced at a scale of 1:1 million.

2. GEOGRAPHY

The ERTS-1 imagery shows, for the first time, accurate outlines of some of the more remote rift valley lakes – for example, Lakes Rudolf, Stefanie, and Rukwa. Shallow and deep areas in the lakes are revealed by brightness contrasts, and deltas are clearly delineated – for example, the two "birds' feet" of the Omo at the northern end of Lake Rudolf (cf. the map of the Omo delta given in Butzer, 1971, Figure 2-1).

Image resolution must be of the order of 50 m or slightly better because the main roads cut through forest show up clearly (e.g., in western Kenya, eastern Malawi, and the Katanga mining belt). Roads cut through bush are less easily distinguished (e.g., in southern Tanzania), and those in scrub or desert are not always possible to locate (e.g., Eritrea and Yemen).

There seems no doubt that geographical factors such as drainage patterns, forest cover, and land utilization can be fruitfully studied from the ERTS-1 imagery of eastern Africa. However, these may require examination techniques different from the simple one used in the present geological mapping. Eye or lens examination was made of black and white prints of ERTS imagery taken in spectral band 2 (NASA Data-Processing Facility band 5), covering the range 6000 to 7000 Å. As shown by U2 aircraft flights over Arizona, and confirmed from the ERTS-1 imagery, geological structures usually show up most clearly in the red.

3. GEOLOGY

The following areas are selected for interpretation: Yemen, Lake Rudolf and eastern Lake Victoria, Lake Tanganyika and Lake Rukwa, and Lake Malawi; and brief comments are given on the Sudan-Uganda border region and on eastern Afar, Ethiopia.

3.1 Yemen

The geology of the Yemen is an important and little-known element in the study of the African rift system, because according to the theory of continental drift, the Yemen was originally situated in the present Afar region of Ethiopia. Thus, the pre-Miocene structures can be expected to be continuous with those of the Ethiopian and Somalian plateaus.

ERTS images 209 to 212* result from the 6 Sep. 72 pass made over central Yemen, from the Yemeni-Arabian border in the north to Bab-el-Mandeb in the south. The main structural lineaments extracted from this imagery are shown on the image reproductions.

Image 212 covers the region of Bab-el-Mandeb, the straits connecting the Red Sea and Gulf of Aden. Several major structural features are revealed on the Yemeni side of the straits: On the western side, in the French Territory of Afar and Issa, abundant Pliocene-Quaternary lavas tend to obscure any fundamental lineaments.

Along the Gulf of Aden coast, east of Bab-el-Mandeb, the line of strato-volcanoes described by Gass, Cox, and Mallick (1965) shows up clearly: Perim Island, J. (Jebel) At Turbah, J. Khariz, and J. Umm Birka (the Aden volcanoes lie east of image 212). These volcanoes belong to the alkali olivine basalt-comendite suite and are of Upper Miocene-Pliocene age (Cox, Gass, and Mallick, 1969). The caldera on

*The image identification numbers used in this report are the frame numbers for given satellite pass days. It is important to note that these are not the official NASA identification numbers, which are rather long-winded and can be found at the right end of the bottom legend on the image reproductions.

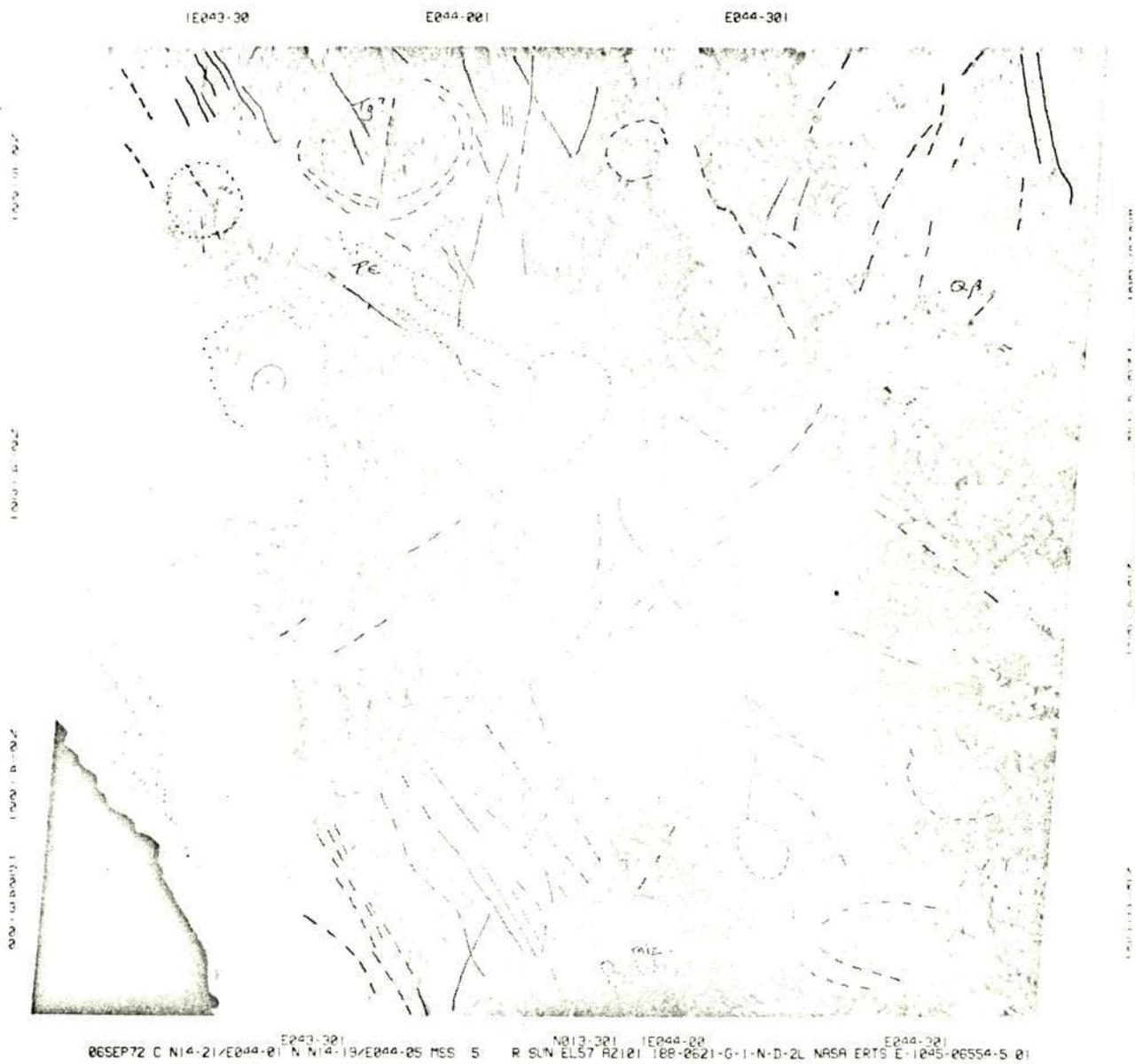


Image 211. ERTS-1 image of Yemen, between Ta'iz and Manakhah, showing upfaulted strip of Precambrian (PC), possible Tertiary granite (Tg), and Quaternary basalt field (Q β).

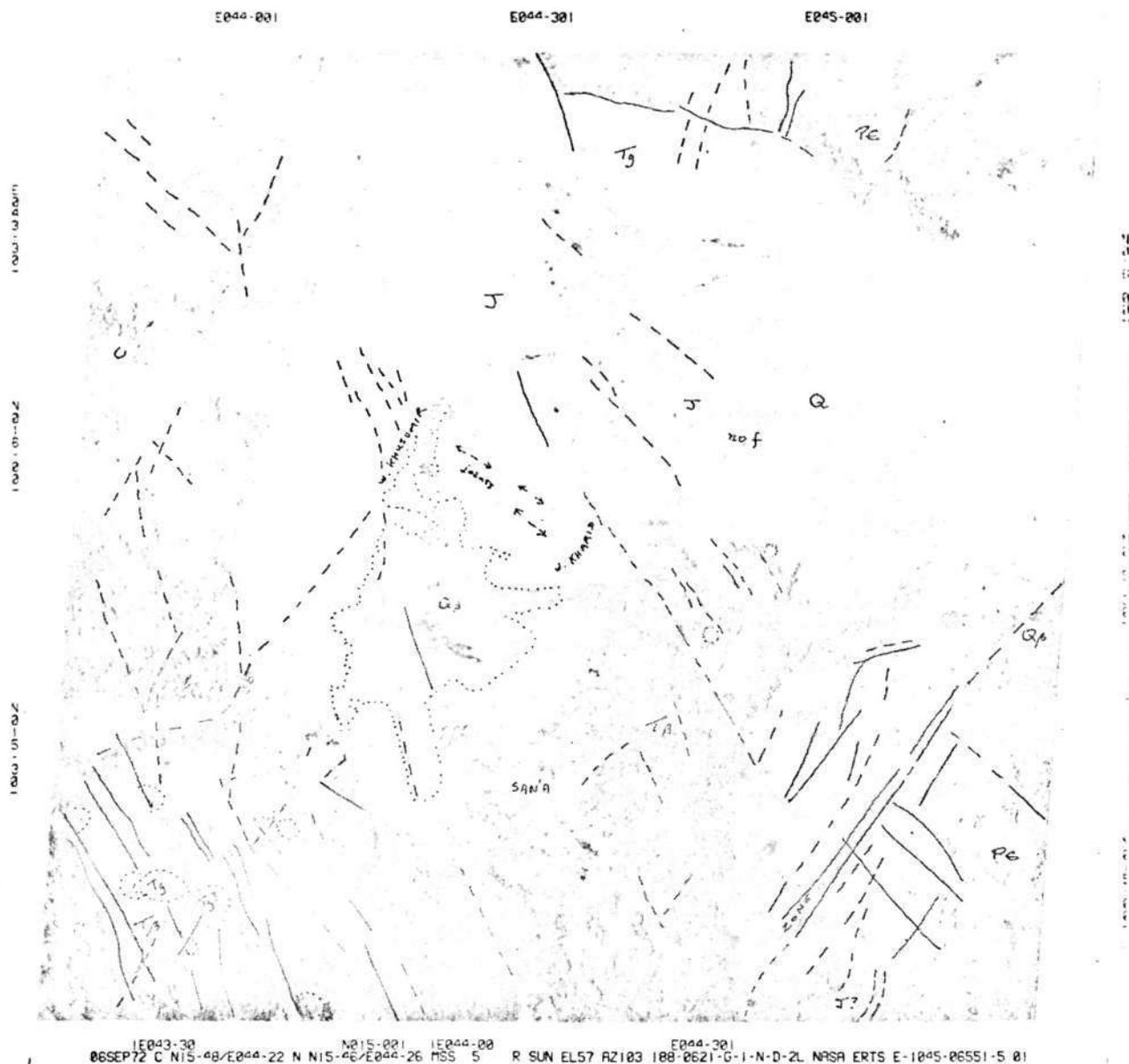


Image 210. ERTS-1 image of the San'a region of Yemen, showing Precambrian terrain (PC), Jurassic limestones (J) with joint directions, Trap basalts (T β), Quaternary basalts (Q β), Tertiary granite (Tg), and Quaternary sediments (Q). The fracture zone east of San'a is indicated by "zone," and "no f" marks where a ground-mapped fault cannot be substantiated.



Image 209. ERTS-1 image of northern Yemen, showing Precambrian terrain (PE), Permian sandstones (P), Jurassic limestones (J), granite (G), and Quaternary sand dunes (Qs).

J. Khariz is easily identified on image 212, but that of the more denuded J. Umm Birka center is obscure (Gass and Mallick, 1968). Another possible late-Tertiary volcanic center is visible 30 km north of J. At Turbah, near the coast of the Red Sea.

Immediately inland from these strato-volcanoes lies a belt of older, flood basaltic lavas, referred to the Eocene(-Oligocene?) Trap Series (Lipparini, 1954; Geukens, 1960). Here, as elsewhere in the Trap Series of Yemen and Ethiopia, circular features are observed on the satellite imagery, probably representing deeply denuded relics of old eruptive centers. Two such centers lie, respectively, 20 km north and 50 km north-northwest of J. Khariz (ERTS image 212), and both have ellipse long axes approximately perpendicular to the NW-SE Red Sea structural trend. Perpendicularity of caldera long axes to rift structures is known from field studies in Ethiopia.

Gass et al. (1965) mention the existence of a monoclinial warp paralleling the northwestern coast of the Gulf of Aden, the seaward pitch being about 5°. Pitching strata are revealed at 13°05'N, 44°10'E on image 212, but a severe, fundamental structure, unreported from ground surveys (e.g., Greenwood and Bleackley, 1967) runs parallel to and immediately north of the broad, coastal monocline. This structure appears to be a fracture zone, trending NE-SW, about 5 km wide and 50 km inland from the Gulf of Aden. At its western end, it peters out against the Red Sea coastal downwarp; to the east, Apollo 9 oblique photography (photo AS9-24-3672) indicates that the zone continues beyond the limit of ERTS image 212, curving north-northeastward into a single fault east of the Yemeni border with Arabia.

The fracture zone appears to be one of intense crustal slicing, without evidence of any horizontal displacements. But while the zone has affected at least the older Trappean basalts, it may be a lineament of long-standing activity, reactivated in a different response with the initiation of the Red Sea and Gulf of Aden rifts. Thus, its latest role may have been to act as a hinge zone for the coastal monocline, though it also forms the southern margin of a Tertiary uplifted plateau block (see below). In these features it rather resembles the marginal gräben of western Afar, Ethiopia (Mohr, 1962). The zone is crossed by NW-SE lineations of Red Sea trend in its central sector, where Geukens (1960) indicates the presence of a single, large fault. Geukens makes the fault a boundary between Trap Series terrain to the northeast and older rocks to the southwest, but the ERTS imagery reveals a more complex situation (see below).

The Red Sea coastal structures, north of Bab-el-Mandeb, are dominated by a chain of arcuate hemibasins, open to the coast. They form a zone about 20 km wide, rising from the coastal plain about 30 km inland from the Red Sea. The basins are arcuate downwarps of the Trap Series basalts and are typically cut by strong antithetic faulting. Very similar features have been described from the eastern margin of the Ethiopian plateau with Afar (Mohr, 1967a, 1971a), and of course the Ethiopian and Yemeni hemibasins would have been contiguous before continental drift (Laughton, 1966). It seems that initiation of the Red Sea here took the form of basins subsiding contemporaneously with extrusion of Trap basalts.

In the "corner" of the southwest Arabian highlands, about 100 km northeast of Bab-el-Mandeb, lies an isolated block of Precambrian rocks whose outcrop is capable of being precisely mapped from the ERTS imagery. Unfortunately, such is the disparity between the imagery and existing maps (e.g., U.S. Geological Survey Map of the Arabian Peninsula, 1963) that without accurate ground information, the writer is unable to assign the appropriate lithologies to the imagery.

From a study of drainage slopes, it can be said that in the northern part of the block the dark terrain stands higher than the light terrain, but in the south the light terrain appears to be a flat-lying plateau dissected by darker canyons. The most probable interpretation is that the lighter terrain is formed of Precambrian rocks capped with subhorizontal sandstones of the Cretaceous Tawilah Group (the Precambrian thus exposes directly in the darker canyons), and that the very dark terrain in the north represents a southerly extension of the previously mapped limit of the Trap Series basalts (Geukens, 1960, 1967). Ground surveys are now required, an ERTS-1 stimulus that was to be expected even before the satellite was launched!

The boundaries of this ancient highlands block are formed to the southeast by the fracture zone described previously, to the southwest by a sinuous fault of Red Sea trend, to the northeast by a belt of Red Sea trend faults that curve to adjust to a Gulf of Aden trend, and to the northwest by a 40-km-long fault precisely parallel to the fracture zone, 40 km to the southeast. Unlike the fracture zone, this boundary is a single, normal fault, upthrown south. It is noteworthy that the northwest boundary of the block is abruptly terminated at both ends by the Red Sea structural trend,

suggesting that Red Sea tectonism has been dominant over Gulf of Aden tectonism in this region, at least during the Neogene and Quaternary.

Proceeding north to ERTS image 211: The city of Ta'iz is situated at 13°34'N, 44°02'E, among Trap Series basalt flows, subhorizontally disposed. South of the city rises J. Sabir, a Tertiary granite massif piercing the Trap Series (Geukens, 1960). This granite is visible on image 211, and 5 km to the west, a twin crater in the Trap Series can be seen. Tertiary granites are numerous in the vicinity of Manakhah, 200 km farther north, where they mark the westerly limit of the highlands Trap Series outcrop (Comucci, 1933; Karrenberg, 1957). Similar granites, of Miocene age, intrude the Trap Series of the Ethiopian plateau-Afar margin (Brinckmann and Kürsten, 1969; Black, Morton, Rex, and Shackleton, 1972).

The Trap Series on image 211 forms dark terrain, without strong structural lineation except near the coastal downwarps. No downwarping is evident on the imagery, north of latitude 14°00'N. Between Ta'iz and San'a, numerous ill-defined circular structures, up to 5 km in diameter, may represent old eruption centers in the Trap Series. The frequency of such centers suggests that in forming the Trap Series, central-type eruptions were at least as important as dike-fissure eruption. This is especially the case in the vicinity of Manakhah (15°02'N, 43°50'E), where the circular features show a tendency to be situated along the subsequent north-northwest-trending margin faults of the Red Sea. Perhaps there is an association between such circular features and the absence of monoclinical warping and dike fissures.

South of Manakhah occurs an upfaulted block of Precambrian rocks, trending southeast, oblique to the south-southeast-oriented coastline of Yemen. The Red Sea narrows in the Yemen region; farther north the typical Red Sea structural trend is NW-SE, and this is extending into the Yemeni highlands in the Manakhah region in the form of block faulting. ERTS image 211 shows some large (15 to 25 km in diameter) circular features to be associated with the faulting of this Precambrian block. The largest, centered at 15°00'N, 43°45'E and traversed by a north-northeast lineament, may be either a tectonic ring structure or, less likely, a granitic intrusion. Two smaller circular features, east and west of the largest circle, are again light colored and may represent silicic igneous centers. But a 20-km-diameter feature immediately south of the Precambrian block is dark colored and presumably marks a big Trappean center.

Commencing north of the Precambrian block, from latitude 15°00'N, numerous fresh faults extend north-northwestward and can be indicated only schematically on image 210. Such relatively new faulting has a very narrow trace on ERTS imagery and can easily be overlooked in deference to older structures that are now emphasized by selective denudation – caution! The intense belt of highland-margin faulting is marked by at least nine small light-colored intrusions that are almost certainly Tertiary granites (Geukens, 1960). The belt passes beyond the western limit of image 210.

In the northeastern corner of image 211, an extensive area around 14°40'N, 44°40'E is covered by the Dhama–Reda Quaternary basalt field (Geukens, 1960). Geukens considers the volcanism to be related to E–W tectonism, but what few lineaments remain unobscured by the voluminous cones and lavas trend NNE–NE. This direction is paralleled by a second Quaternary basalt field, 100 km farther north (see below). The Dhama–Reda tectonism forms a weak but persistent tectonic grain that extends southwest to the Ta'iz region, where it may be related to the outcropping of NNW–SSE strips of Precambrian rocks.

About 50 km east of San'a, and clearly shown on ERTS image 210, occurs another intense fracture zone of similar form to the one near the Gulf of Aden coast. This fracture zone was recognized by Geukens (1960) and termed the Sirwah–Marib fracture zone. It averages 3 km in width and trends northeastward (this also happens to be the trend of the Gulf of Aden transform faults). The zone is clearly delineated for 50 km, and farther northeast it is superimposed by lines of Quaternary basalt centers. Small parallel lineaments occur on either side of the zone. Some NNW–NW lineaments cross the zone without any lateral displacement, so again there has been no wrench movement along a major fracture zone. And again, the Sirwah–Marib fracture zone separates Precambrian (and Mesozoic) terrain from Trap Series volcanics, suggesting that in many sectors the margin to Tertiary volcanism was determined by tectonic factors, and not merely by overlap.

Deformed Precambrian and Mesozoic rocks occur immediately southeast of the Sirwah–Marib fracture zone. To the northwest, the Oligocene–early Miocene Trap Series (Brown, 1970) extends for 100 km, lying on undisturbed Jurassic limestones.

The limestones show jointing in a NNW–NW direction, parallel to the young, highland-margin faulting described above.

Directly north of San'a, there is a large Quaternary basalt field between the Wadis Khusukir and Kharid. Numerous small cones in this field are associated with north–northwest fractures, and prelava and postlava fractures can be observed on the ERTS imagery. The most recent lavas have broken out eastward. Despite the young north–northwest faults, the San'a Quaternary basalts, like other occurrences of such lavas in Yemen, are situated on a NE–SW lineation belt exposed in the Mesozoic sediments and Trap Series 50 km west of San'a, although in this instance the lineation is admittedly weakly developed.

Farther north from San'a, on ERTS image 209, the west–northwest–trending J. Barach fault (Geukens, 1960) limits Precambrian and trough–faulted Permian sandstones in the north, against Jurassic limestones to the south. This extensive fault, traversed by later, smaller faults of NE–SW trend, can now be mapped accurately for the first time. The Permian Wajid Sandstone is preserved in north–northwest–faulted troughs where these intersect the J. Barach fault. The Precambrian terrain north of the J. Barach fault (the Medina Series of Geukens (1960)) contains light-colored, circular features, 5 to 15 km in diameter. It is not yet known whether these are related to the problematic Mafflouk laccoliths intruding the Jurassic sediments, south of the J. Barach fault (Geukens, 1960).

In summary, the ERTS satellite images of the Yemen confirm the fine reconnaissance ground surveys of Geukens (1960), but inevitably add very considerably to this work at the 1:1 million mapping level. The writer considers that the ERTS imagery of Yemen is another giant step.

ERTS image 223 (10 Sep. 72), covering northern Eritrea, can conveniently be appended to this discussion, as it presents the opposing coastal plain and hinterland across the Red Sea from Yemen.

The margin between the coastal plain, a zone whose downwarping is not revealed on the ERTS image, and the Eritrean highlands is clearly visible. This margin is



Image 223. ERTS-1 image of northeastern Eritrea, showing Trap Series basalts (T β) on the regionally exposed Precambrian. A young fault in the west half of the image is indicated by "Qf." Note the site of Asmara, hidden under pollution cloud.

presumed to be formed by major faulting, upthrown west, but the (Tertiary) fault traces are now buried beneath outwash fan deposits. The margin shows left-en-echelon development near latitude 16°30'N.

The highlands are entirely comprised of Precambrian rocks, surficially lateritized before extrusion of the Trap Series occurring farther south. The dominant tectonic grain is north-northwest, approximately parallel to the Red Sea structural trend (Porro, 1935), but regional virgations in the foliation trend turn to form an important north-northeast lineation. The problem of distinguishing foliation trend from lithological strike in Precambrian terrain, as evidenced on aerial photographs or satellite imagery, is usually a difficult one to solve (Greenwood and Bleackley, 1967), but with further experience it is hoped to use the ERTS imagery for this purpose.

At 15°55'N, 38°45'E, northeast of Keren, an 8-km-diameter circular structure occurs. Its nature remains unknown, but it is likely to be a late-stage Basement granitic intrusion, rather than a Tertiary granite of Yemeni type.

At the southern margin of ERTS image 223, the most northerly preserved remnant of the Ethiopian Trap Series, in the vicinity of Asmara, is clearly outlined and confirms the mapping of Dainelli and Marinelli (1912). The Trap Series in Eritrea is of Lower Miocene age (Mohr, 1967a, b; Brown, 1970), matching the age of the Trap Series in northern Yemen.

Although not immediately relevant to the present discussion, it is of great interest that the ERTS pass of 29 Sep. 72 (images 024 to 026) has revealed the presence of at least one massive lineation belt in the well-exposed Precambrian of Eritrea. This forcibly expressed belt is about 5 km wide and extends for at least 300 km from northern Eritrea to the limit of the present ERTS imagery in northern Tigray; Andreatta (1941) mentions the occurrence of mylonites and cataclasites in western Eritrea, but he did not suspect the newly identified lineament in his tectonic classification of the Eritrean Precambrian. It curves from possibly a Red Sea trend at latitude 18°00'N (longitude 38°00'E) to pass south into Ethiopia along the eastern margin of the J. Hamoet highlands. Then it begins to curve round to a S30°W trend, crossing the Baraka river at latitude 15°45'N and the Mareb (Gash) river near

Aycota at latitude 15°08'N. The southwestward projection of this profound lineament beyond the limit of ERTS image 026 is directly through Omm Agher and along the western escarpment of the Ethiopian plateau overlooking the Sudan plains.

3.2 Lake Rudolf-Kavirondo Gulf

The ERTS-1 pass of 10 Sep. 72 traverses the western side of Lake Rudolf, Mt. Elgon (cloud covered), and the eastern side of Lake Victoria, imaged on frames 231 to 234. Thanks to the excellent field mapping of the Geological Survey of Kenya, the ERTS imagery can be used to search for and add further knowledge to several important geological features associated with the African rift system.

In the north, image 231 covers the northern end of Lake Rudolf. Although a 20% cloud cover obtrudes, the shores of this lake can be accurately mapped for the first time, and also the Omo delta with its two "birds' feet." The northward extent of the Omo delta flats, the site of Pleistocene hominid discoveries, can be mapped but is partly obscured by clouds.

Strong, recent tectonism runs meridionally about 50 km east of Lake Rudolf. This is the late Tertiary-Quaternary faulting of the Kinu Sogo belt, which extends from the Suguta trough at the south end of Lake Rudolf (not covered by this pass) northward via the western edge of the Chalbi desert to the western margin of the Lake Stefanie graben (Baker, Mohr, and Williams, 1972). Near Lake Stefanie, the faulting is dense and can be indicated only schematically on image 231. Of interest is the discovery of a superimposed NE-SW and E-W tectonism immediately southwest of the lake: Future imagery centered on Lake Stefanie should indicate the extent of these cross fractures.

Along the western side of Lake Rudolf, meridional faulting has produced the 15-km-wide Precambrian horst of the Labur hills, and this horst faulting continues via Upper Miocene volcanic blocks - for example, the phonolite-nephelinite Lodwar and Kamutile centers - south as far as latitude 2°15'N. Thus, the entire western side of Lake Rudolf is margined by this faulting, but it is obscured or obliterated where the remarkable arcuate valley of the Turkwel river turns to reach Lake Rudolf at latitude 3°10'N. No fault traces can be observed on image 232 to connect the horst segments to



Image 231. ERTS-1 image of the northern Lake Rudolf region.



Image 232. ERTS-1 image of the lower Turkwel valley and southern Lake Rudolf region, showing Precambrian terrain (PE), Tertiary basalts (Tv), Miocene nephelinite-phonolites (M_{NP}), Miocene basalt (M_β), and Pliocene basalt (P_β). Some young faults are labeled "Qf."

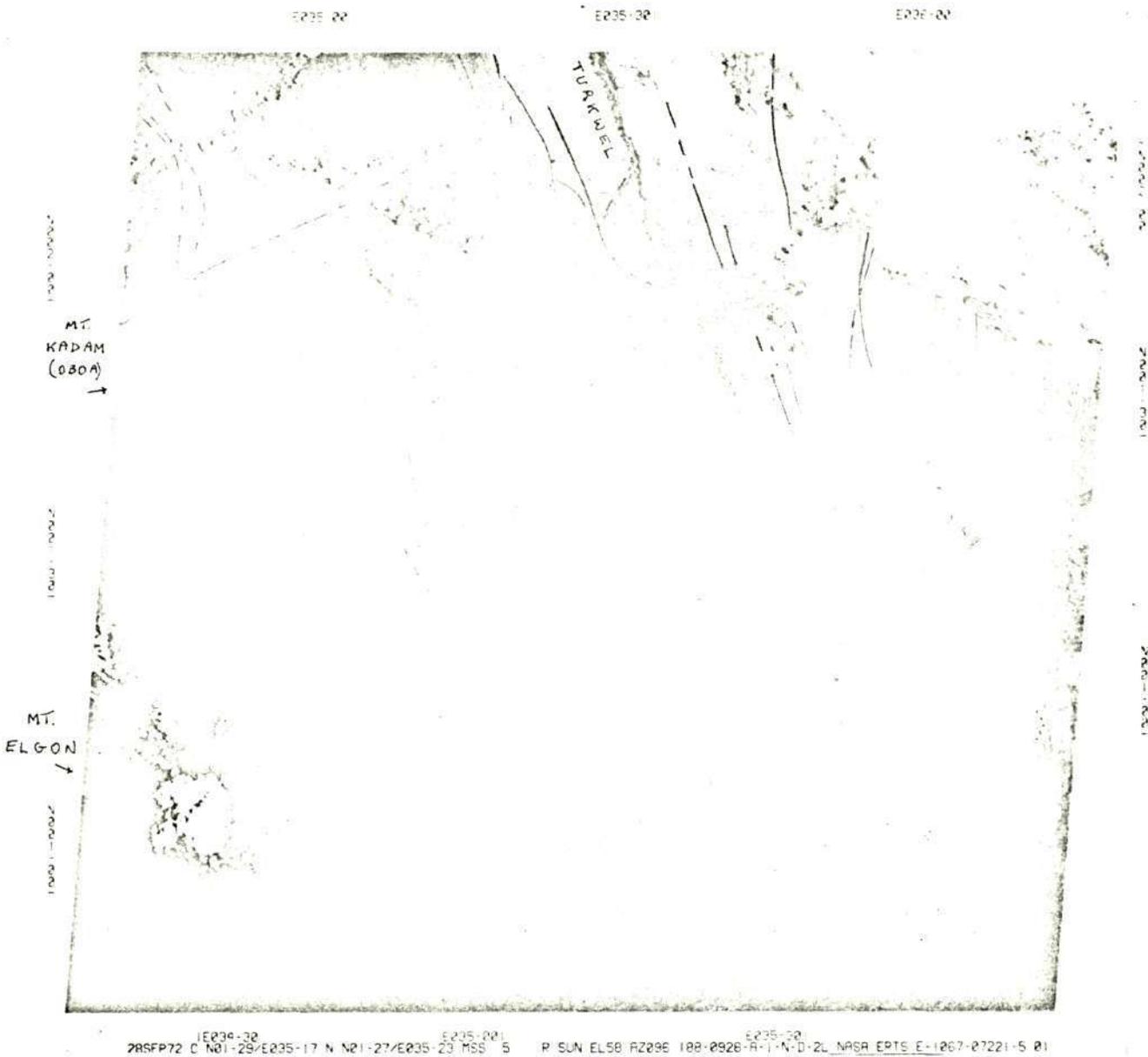


Image 033. ERTS-1 image of the western margin of the Gregory Rift, showing the sharp conjunction of the Turkana and Kerio faulting.

the north and the south, suggesting that the faulting predates the surface sediments of the Turkwel.

Similarly, the strongly expressed Turkana fault, trending north-northwest close to longitude 35°E on image 232, cannot be traced with certainty across the fluvial plains of the Lorugumu. If there is recent faulting on this side of Lake Rudolf, it is not manifested in any large displacements or extensive traces. The Turkana fault can be observed in the Miocene basaltic massif of the Muruasigar hills, north of the Lorugumu valley, and also south along the western margin of the Turkwel valley.

Fairburn and Matheson (1970) have mapped the Lorugumu valley region in detail, and the ERTS imagery generally confirms the identification of their lithological boundaries. However, their subdivisions of the Precambrian are less easy to distinguish -- for example, in the Okabaa syncline at $2^{\circ}35'\text{N}$, $35^{\circ}10'\text{E}$. Fairburn and Matheson (1970, pp. 47-48) infer the presence of faults on the floor of the Turkwel valley, but none of these can be identified on the ERTS imagery. Repeat imagery of this region is desirable, with different sun angles.

At the western edge of image 232, the Moroto nephelinite-phonolite cone clearly exhibits its central intrusion, in the form of an "erosional caldera" (Varne, 1967). Despite its alignment with centers of similar magma type and age (Nixon and Clark, 1967), no strong linking faults can be identified.

Image 233 gives the first ERTS picture of a well-known sector of the Eastern Rift (Baker *et al.*, 1972). Image 033 (28 Sep. 72) covers the same area and, for reasons not yet understood, brings out the fundamental structures more clearly. The Turkana fault zone continues south to the Cherangani hills, where it is intercepted by the Quaternary faulting of the Elgeyo escarpment, forming the western margin of the Gregory Rift. The regional interplay between the south-southeast-trending faults of the upper Turkwel valley (including the Turkana fault) and the remarkably linear north-northeast-trending faults of the Kerio valley (including the Elgeyo escarpment) is revealed for the first time. Despite some local adjustments through curving faults, the Kerio structures appear to cut off the Turkwel faults abruptly. The inference is that the faulting of the upper Turkwel valley, though locally rejuvenated, belongs to an earlier phase of rifting with a somewhat different stress field than later developed for the main phase of Quaternary rifting.

Future imagery of the Gregory Rift is awaited, to see if a south-southeastward projection of the Turkwel faulting can be identified along the complex eastern escarpment near Lake Hannington (Baker et al., 1972, Figure 12), and again to see whether it may be cut across by fundamental, linear Quaternary faults.

East of the Cherangani hills, the rift floor is first encountered in the 20-km-wide Kerio graben, which is separated from the main part of the rift floor farther east by the Kamasia-Tiati platform. This platform appears to be cut by small, sinuous fractures that are too short and numerous to be indicated in image 033. McClenaghan, Weaver, and Webb (1971) indicate the presence here of a Pliocene zone of monoclinial warping.

On the plateau west of the rift, a sinuous north-northwest tectonic grain in the Precambrian Mozambique Belt is exposed along the Kenya-Uganda border, crossed by linear NE-SW fractures in the vicinity of the Oboa (Kadam) nephelinite center. The Miocene phonolites of the Uasin Gishu plateau, south of the Cherangani hills, appear to be virtually unfractured.

The next most southerly image, ERTS 234, and the last to be discussed in this section, is centered on the Kavirondo Gulf, eastern Lake Victoria. This Gulf occupies a small rift valley, transverse to the main Gregory Rift (Shackleton, 1951; Baker et al., 1972).

A fundamental crustal boundary extends southward from Mt. Elgon, marked by the Nandi escarpment (Sanders, 1965). This escarpment is due to a "great thrust and wrench-fault zone which is the westernmost expression of penetrative eastward dipping thrusts" affecting the Precambrian rocks 70 km farther to the east (Sanders, 1965, p. 4). Within and west of this zone are exposed Nyanzian granitic rocks; to the east the Nyanzian is increasingly covered by the metasediments of the Mozambique Belt. After some decades of geological debate, it has been established that the Nandi escarpment is not an expression of normal faulting.

The Nandi escarpment shows up clearly on ERTS image 234, and as mapped on the ground, it turns from southeast to south to meet the northern escarpment of the Kavirondo rift perpendicularly. The Nandi faulting has not been traced farther on the

ground, but ERTS image 234 reveals a small volcanic center within the Kavirondo rift on a projection of the Nandi faulting; and south of this rift some definite lineaments continue due south, close to the boundary of the Bukoban (to the west) and the Mau phonolites (to the east). This lithological boundary shows up quite well on the ERTS imagery.

The junction of the Kavirondo and Gregory rifts is cloud covered on image 234. The western sector of the Kavirondo rift shows the northern fault, as mapped by Shackleton (1951), though the western continuation of this fault as a monoclinial flexure to the shores of Lake Victoria cannot be distinguished. Along the southern margin of the rift, the linear Sondu escarpment shows up clearly, but again its western continuation as the Kaniamura escarpment – and also its easterly extent into a monoclinial flexure (Shackleton, 1951) – cannot be certainly identified. On the southern shores of the Kavirondo Gulf, the Homa carbonatite center (LeBas, in preparation) shows up clearly, but the Kisingiri centers are partly obscured by cirrus cloud and cannot be distinguished.

3.3 Lake Tanganyika

Lake Tanganyika lies within the Western Rift. The Cainozoic* faulting that bounds this lake has frequently been shown in schematic form (e. g., McConnell, 1972; King, 1970), but detailed structural mapping of this region is limited. Lake Tanganyika is bordered by Tanzania, Zaire (Congo), Burundi, and Zambia, and the value of an integrated mapping scheme using ERTS imagery is correspondingly emphasized.

The ERTS pass of 13 Sep. 72 (images 181 to 184) covers Lake Tanganyika as far south as latitude 7°S. The eastern portion of Lake Rukwa (image 240) was covered on 10 Sep. 72, so that there currently remains a gap between longitudes 30°30'E and 32°E.

The northern end of Lake Tanganyika (ERTS image 181) is contained in a 20-km-wide graben; the trend is N–S where occupied by the lake but curves to the north-northwest up the Ruzizi valley. The evidently young Quaternary faulting that bounds

*Without wishing to raise Cain, this writer demurs from Cenozoic. He is not aware that our's is an era empty of life, not just yet anyway. Cainozoic more accurately reflects the graveyard of our ancestors, rather than the cenotaph of their hopes.



Image 182. ERTS-1 image of the north-central Lake Tanganyika region.

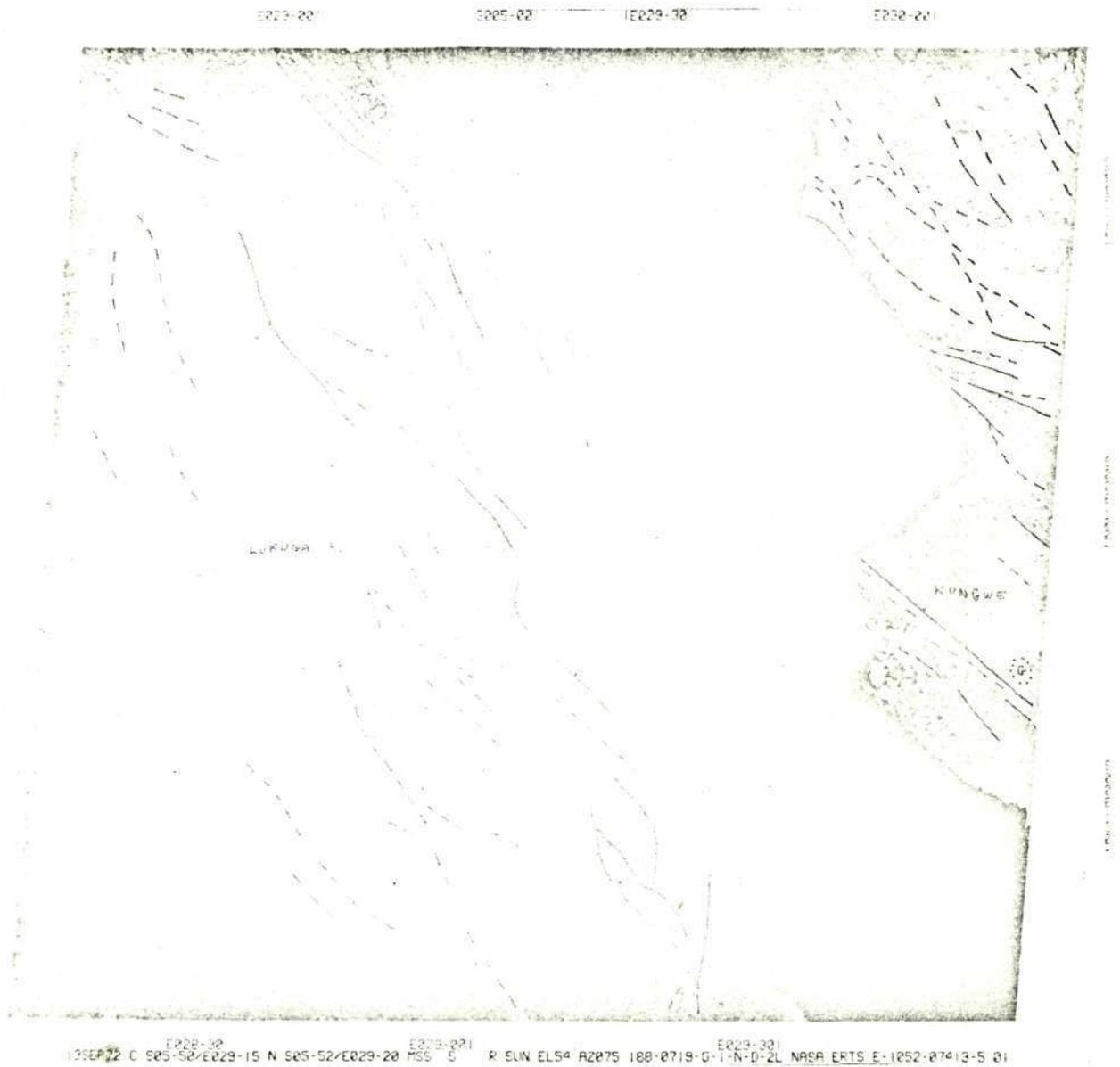


Image 183. ERTS-1 image of the central Lake Tanganyika region, including upper Lukuga valley and Kungwe horst (with granite "G").

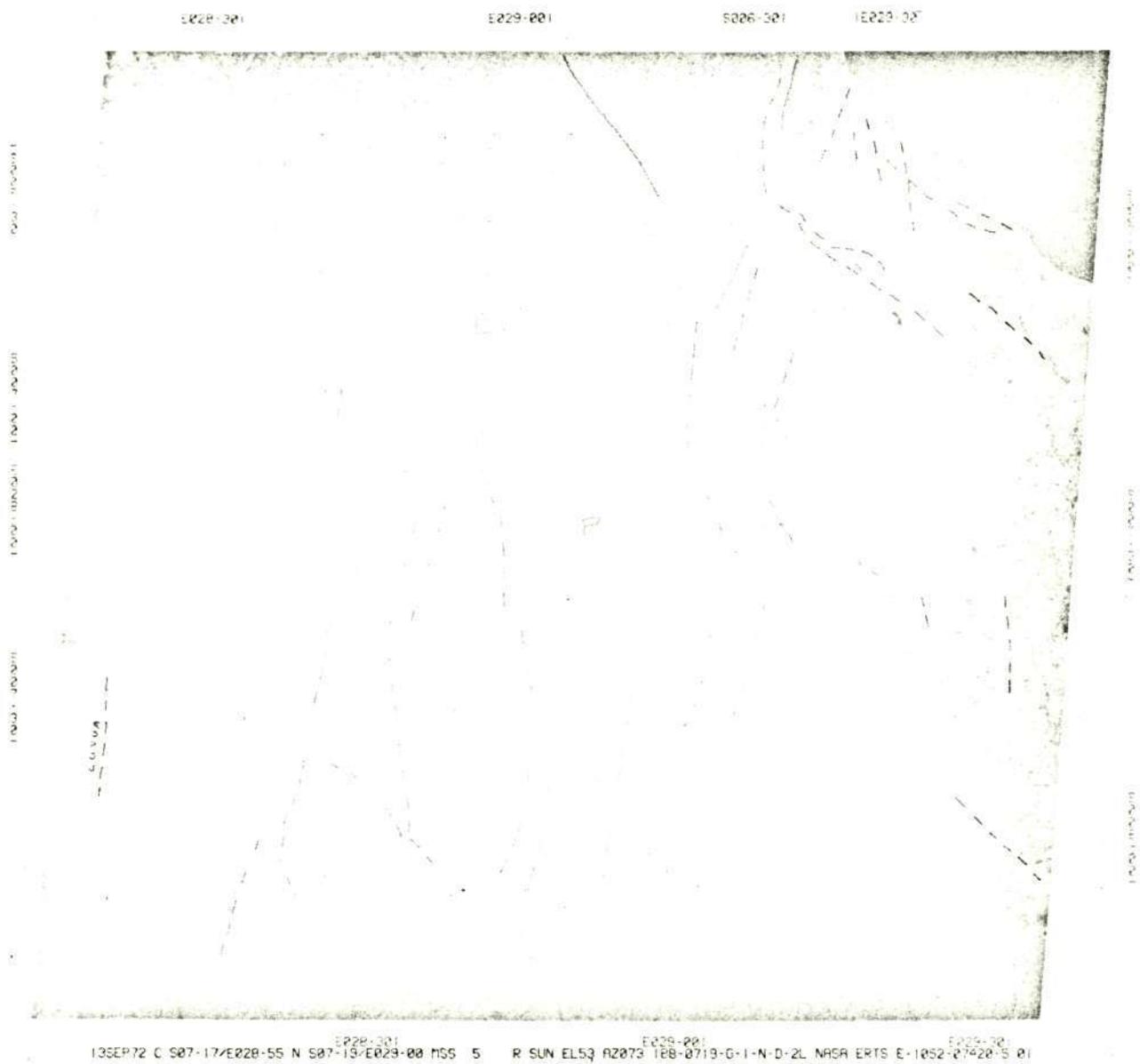


Image 184. ERTS-1 image of the region southwest of Lake Tanganyika, showing Kibaran porphyries (P) contrasting with Bukoban terrain (Bu).

this graben is axial to the much larger, 60-km-wide trough of the Lake Tanganyika rift. Thus the margins of this rift, each about 15 to 20 km across, comprise dissected slopes that decline rather regularly from the plateau rim down to the graben floor. Major faulting within these marginal zones generally appears to be rare. Whether major faulting determines the plateau rims cannot be stated from image 181, where cloud completely obscures this ground, but the precisely arcuate plan of the eastern Burundi rim of the Tanganyika rift suggests that it is the result of tectonic control rather than an accident of denudational recession. It is also possible that the Lake Tanganyika rift represents a young graben within an older warped trough — future ERTS imagery may help decide on this point.

The freshness of the faulting at the northern end of Lake Tanganyika, and along the Ruzizi valley, conforms with this region being the most seismically active in the entire African rift system, although the density of faulting is much less here than it is in many parts of the Eastern Rift. Fairhead and Girdler (1971) have plotted some recent epicenters along the eastern boundary of the northern Tanganyika graben.

In Burundi, well to the east of the lake, broadly folded Burundian conglomeratic phyllites that were involved in the Kibaran tectonism about 1300 m.y. ago (Cahen, 1970) are exposed. The structural grain of these rocks, reflected in the drainage pattern, is observed to run NE-SW, distinctly oblique to the Tertiary rift faulting and noted as being so by McConnell (1972). Thirty kilometers southeast of Usumbura (Bujumbura), arcuate tectonism is developed on the rim of the rift, suggestive of anticlockwise rotational movement.

Northwest of Lake Tanganyika, and along the immediate eastern fringe of the lake, runs the Rusizian gneiss belt, a product of the Ubendian tectonic episode some 2100 m.y. ago. The structural grain of this belt is N-NNW and is closely paralleled by the rift structures at the north end of the lake. But the same belt turns NW-SE farther south, cutting sharply across the rift trough. This raises the vexed question, which cannot be gone into here, of whether the rift valleys of Africa are independent structures that merely take advantage of the Precambrian crustal grain where suitable (Baker et al., 1972), or whether the rift valleys and Precambrian structures are

intimately related to the point of being expressions of the same, long-standing sub-crustal process (McConnell, 1972). Nevertheless, accumulated evidence from ERTS imagery of the Western Rift (in the Eastern Rift, the Precambrian rocks are largely covered by Cainozoic volcanics) may well prove critical in this argument.

Near latitude 4°S , the 8-km-wide Cape Banza horst protrudes north from the western shore of Lake Tanganyika. It is separated from the western marginal zone of the rift by a shallow graben (Burton Bay) 15 km in width. The structural alignment of the horst suggests a continuity from the Rusizian gneiss belt at the northeastern end of the lake. South of Burton Bay, the structural grain curves from N-S to NW-SE and enters the lake. This curvature is an adjustment to the regional NW-SE trend of the Ubendides (Cahen, 1970), and it is notable that it occurs where the younger Burundian-Kibaride tectonism attempts (but fails) to traverse the Ubendides. No major rift marginal fault can be detected on ERTS image 182, south of Burton Bay (cf. McConnell, 1972).

The ERTS imagery gives sharp expression to a narrow zone of Cainozoic faulting at latitude 5°S on the eastern side of Lake Tanganyika. This faulting trends NW-SE, upthrown northeast, and bounds an uplifted block northeast of the Kiyimbi River. The Kiyimbi faulting precisely follows the Precambrian Ubendide grain of eastern Zaïre. South of latitude 5°S , the Kiyimbi faulting is progressively more strongly matched by the parallel development, about 10 km to the northeast, of southwest-upthrown faulting along the lake shore. Thus a long, narrow horst extends along the western margin of the lake, to just north of the Lukuga effluence, and is on a precise alignment with the Kungwe horst on the eastern side of the lake (see below). Here, between latitudes $5^{\circ}30'\text{S}$ and $6^{\circ}00'\text{S}$, the Lake Tanganyika trough exhibits its renowned "kink" in traversing across two parallel NW-SE structural depressions.

Forty kilometers south of Bujumbura, the eastern shoreline of Lake Tanganyika turns abruptly from the meridional, Rusizian trend to an 80-km-long stretch trending SSE-SE. The abruptness of this turn and the linearity of the shore south of the turn are not indicated on existing maps. Despite the linear trend, there is no evidence on the ERTS imagery (image 182) for any controlling NNW-SSE faults. Indeed, the Burundian terrain of the hinterland to the east intercepts the lake with a NNE-SSW structural trend.

The eastern shoreline of Lake Tanganyika makes another abrupt turn, 50 km north of Kigoma, back to a N-NNE trend. Here, the Cainozoic faulting determining the shoreline is closely associated with a major Precambrian lithological boundary, separating Burundian rocks to the west from the late-Precambrian Bukoban to the east. The Bukoban has been mapped by the Geological Survey of Tanzania as virtually undeformed, sedimentary clastic formations, and the lack of deformation is consistent with a structural featurelessness on ERTS image 182, east and northeast of Kigoma (4°52'S, 29°38'E). Nevertheless, the Burundian-Bukoban boundary is not outstanding, and to map it from the ERTS imagery may prove difficult.

South of Kigoma, Bukoban terrain shows a north-northwest structural grain that intensifies toward the coast at latitude 5°30'S. This grain may be in part, or even entirely, due to the Cainozoic faulting that forms the northeast margin of the Ubende graben (McConnell, 1972, Figure 4). Future ERTS imagery to the east of Lake Tanganyika will help resolve the problem of the eastward continuation of this graben.

The southern margin of the Ubende graben is formed by the Kungwe horst, which bulges westward into Lake Tanganyika at latitude 6°S. The horst is composed of Ubendian rocks, and the Cainozoic faults follow the NW-SE Precambrian structural grain exactly. The Kungwe horst is on the precise southeast-projecting alignment of the NW-SE horst on the western side of the lake, north of the Lukuga effluence; and in fact, connection occurs in the form of a shallow sill in the lake (R. B. McConnell, 1972, personal communication). It is in traversing this sill that Lake Tanganyika obtains its kink in geographical plan. No example of a transverse NE-SW lineament can be observed on either side of the lake in the vicinity of the kink, though ERTS passes to either side of the present one are required to substantiate this conclusion.

The ERTS pass of 13 Sep. 72 leaves Lake Tanganyika, southeast of the Kungwe horst, and reaches the northern fringe of the Lake Mweru basin. The Karroo sediments of the Lukuga valley, and the extensive Bukoban terrain to the south, are marked by a weakly developed NNW-NW lineation of Ubendian trend. Along the shoreline of Lake Tanganyika, south of the Lukuga effluence, strong but short arcuate faulting

forms the rift margin. This faulting turns from north-northwest to north-northeast, where, south of latitude 6°30'S, a wide belt of Kibaran volcanic porphyries is encountered (Cahen, 1970). Their light color and the lack of cultivation distinguish these Precambrian volcanics quite clearly from the neighboring lithology. The marked NNE-SSW structural grain of these volcanics extends to the eastern side of Lake Mweru, a site of active seismicity (Fairhead and Girdler, 1971).

Farther west, the ERTS pass of 14 Sep. 72 (images 086 to 089) reveals the strong NNE-SSW faulting along the eastern side of the Upemba graben (Cahen, 1954). It is hoped that future ERTS imagery will show the precise relationships of these south-southwest-trending offshoots to the Western Rift itself.

The ERTS pass of 10 Sep. 72 (image 240) and, more recently, that of 29 Sep. 72 (images 063 and 064) cover the greater part of Lake Rukwa. The Rukwa rift links the Lake Tanganyika rift with the Lake Malawi rift, but the fault pattern of this link is not well known.

Unfortunately, images 063 and 064, covering the western end of Lake Rukwa and the southern tip of Lake Tanganyika, are interfered by stratocirrus cloud. Image 240, though of low contrast, is cloud free and covers the eastern end of Lake Rukwa and the Mbeya region.

The linear northern shore of Lake Rukwa is determined by a major northwest-trending rift fault, upthrown northeast. Whether this fault continues to the Ubende graben (see above) cannot be determined from image 063, but to the southeast it bounds the Mbeya horst (Brown, 1962) immediately before meeting the NE-SW Usangu fault of the Eastern Rift at Mbeya town. The southwestern margin (Songwe scarp) of the Mbeya horst appears offset en-echelon from the main Rukwa escarpment, and is the site of a peculiarly linear Middle Cretaceous carbonatite (Brown, 1964).

The Songwe and Usangu scarps meet without any adjusting faults. However, the Rukwa faulting would appear to be more fundamental here, because the Neogene-Quaternary volcanic center of Rungwe (Harkin, 1960) lies on its projection, 15 km southeast of the scarp termination at Mbeya. The structural grain of the cratonic (> 2500 m.y.) Precambrian rocks of the Mbeya horst parallels the Rukwa escarpment.

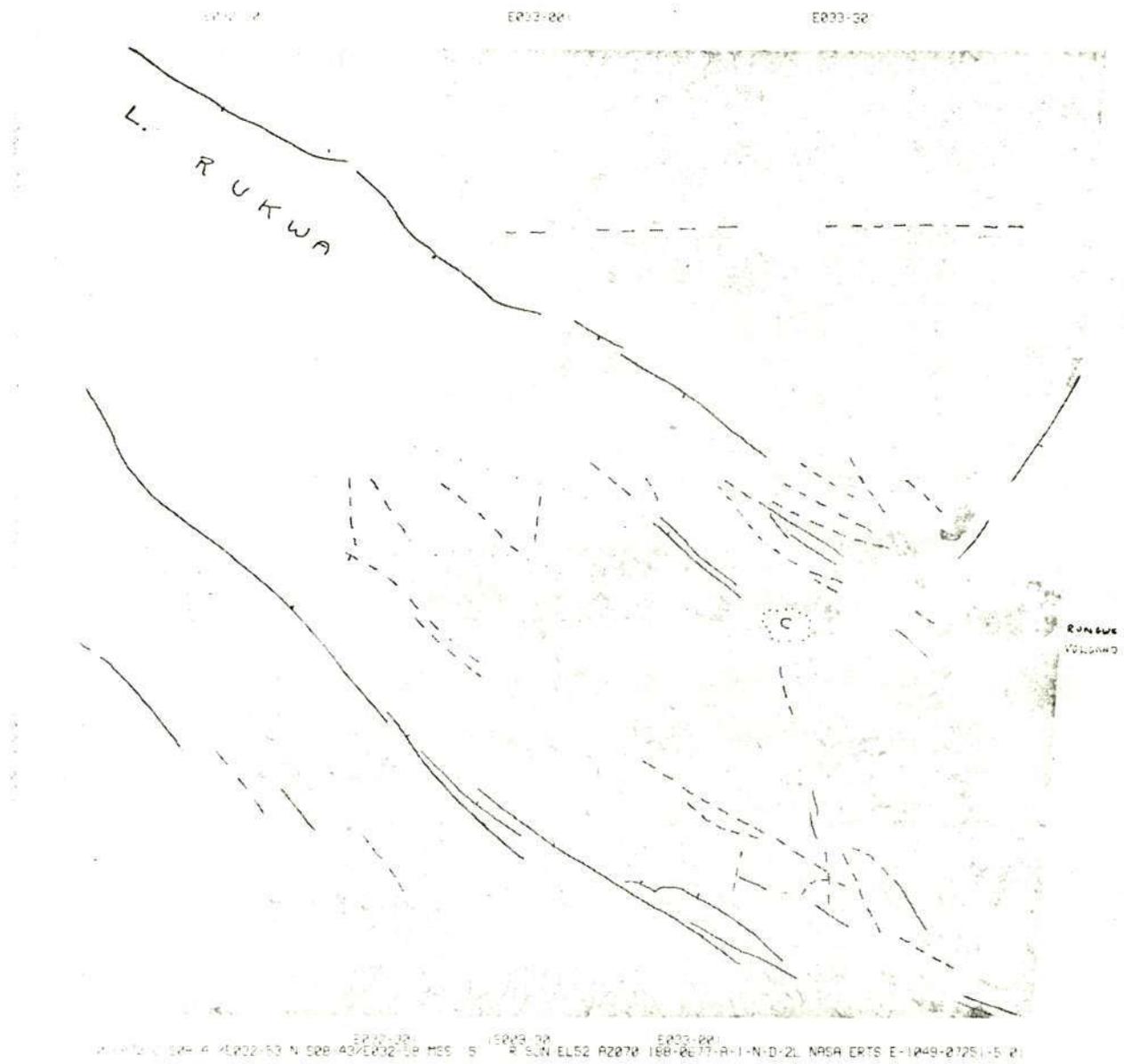


Image 240. ERTS-1 image of the eastern Lake Rukwa region and the Mt. Rungwe volcanic center. Panda Hill carbonatite complex is indicated by "C".

By contrast, no definite lineations of NE-SW trend can be identified crossing the Rukwa rift south of Mbeya (cf. McConnell, 1972, Figure 4), though beyond this rift commences the NE-SW Luangwa rift (deSwardt, Garrard, and Simpson, 1965) with its notably arcuate boundary structures (images 041 to 043, 28 Sep. 72).

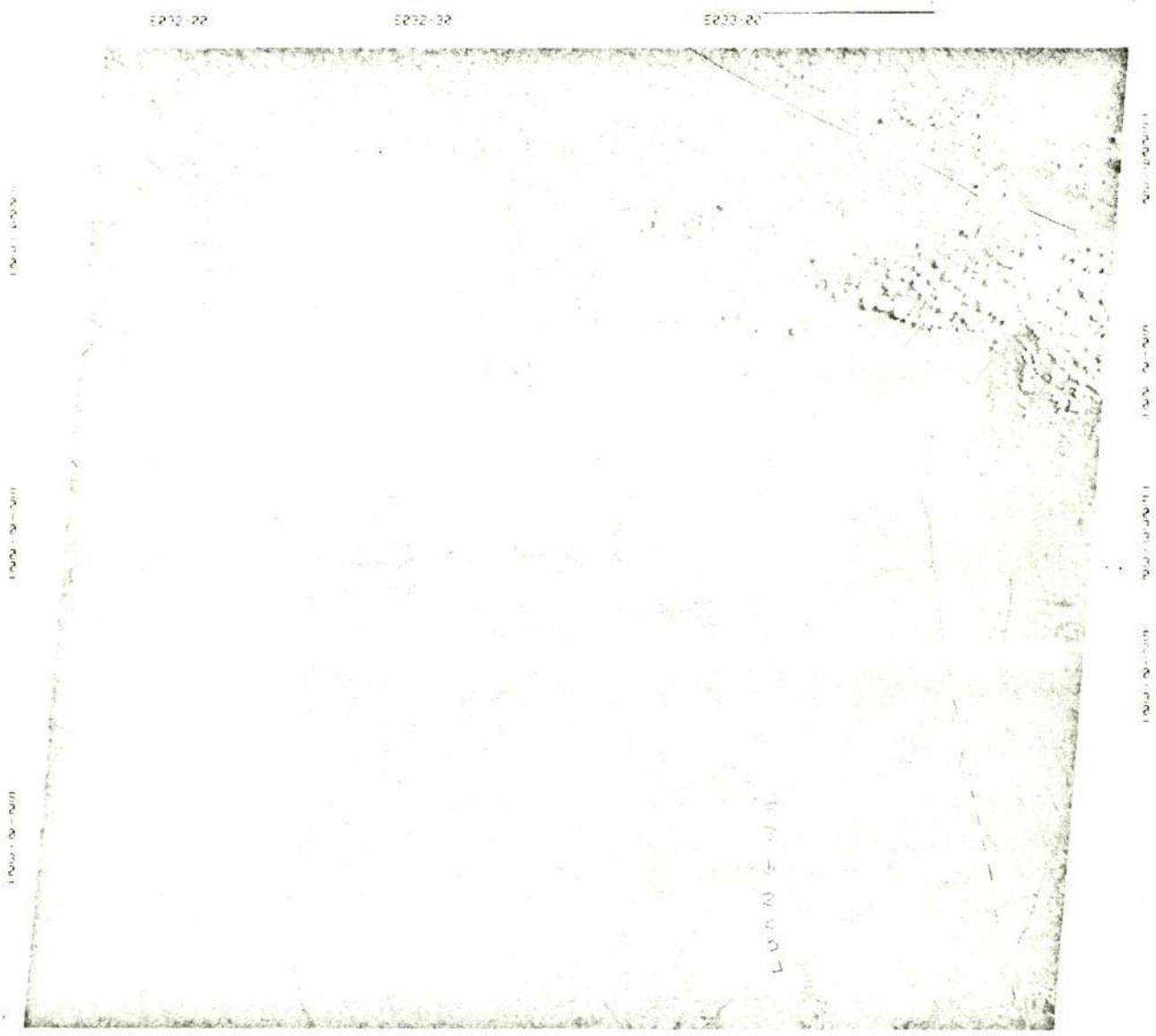
Both the Rungwe lavas and the Panda Hill carbonatite show up well on the ERTS imagery. However, the Mbozi block, immediately south of Lake Rukwa (Pallister, 1971), is not delineated.

The southern margin of the Rukwa rift is formed by a powerful and persistent fault, but gently curvilinear, in contrast to the linear northern-margin fault. The plateau south of the southern margin is formed of Ubendide granitoid metasediments and metavolcanics (McConnell, 1972) whose structural grain again parallels that of the rift, though the grain is very weakly expressed on the ERTS imagery (240 and 064). Discussion of major virgations at the southern end of Lake Tanganyika (image 064) is deferred until cloud-free imagery is available.

The ERTS imagery of the Lakes Tanganyika and Rukwa rifts shows that where the Precambrian structural grain is parallel to that of the Cainozoic rift faulting, the latter is persistent, with few or no en-echelon offsets. But where the regional rift tectonism begins to turn from parallelism with the Precambrian structures, the rift faults are short and frequently offset, or are strongly arcuate. Where markedly oblique to the Precambrian structures, rift faults tend to resume a persistent linear trend, in concordance with the regional rift pattern.

3.4 Lake Malawi

ERTS-1 imagery of the Lake Malawi (Nyasa) rift is currently limited to the passes of 8 and 26 Sep. 72 (images 020 to 022 and 055 to 058, respectively). These passes are almost duplicates and cover the lake from its eastern side at latitude 11°S to the highlands southwest of the lake.



E212-22 E222-22 E232-22
 28SEP72 C S10-24/E212-22 N S10-25/E222-22 MSS 5 R SUN EL55 A2278 188-0928-A-1-N-D-2L NASA ERTS E-1267-07253-5 01

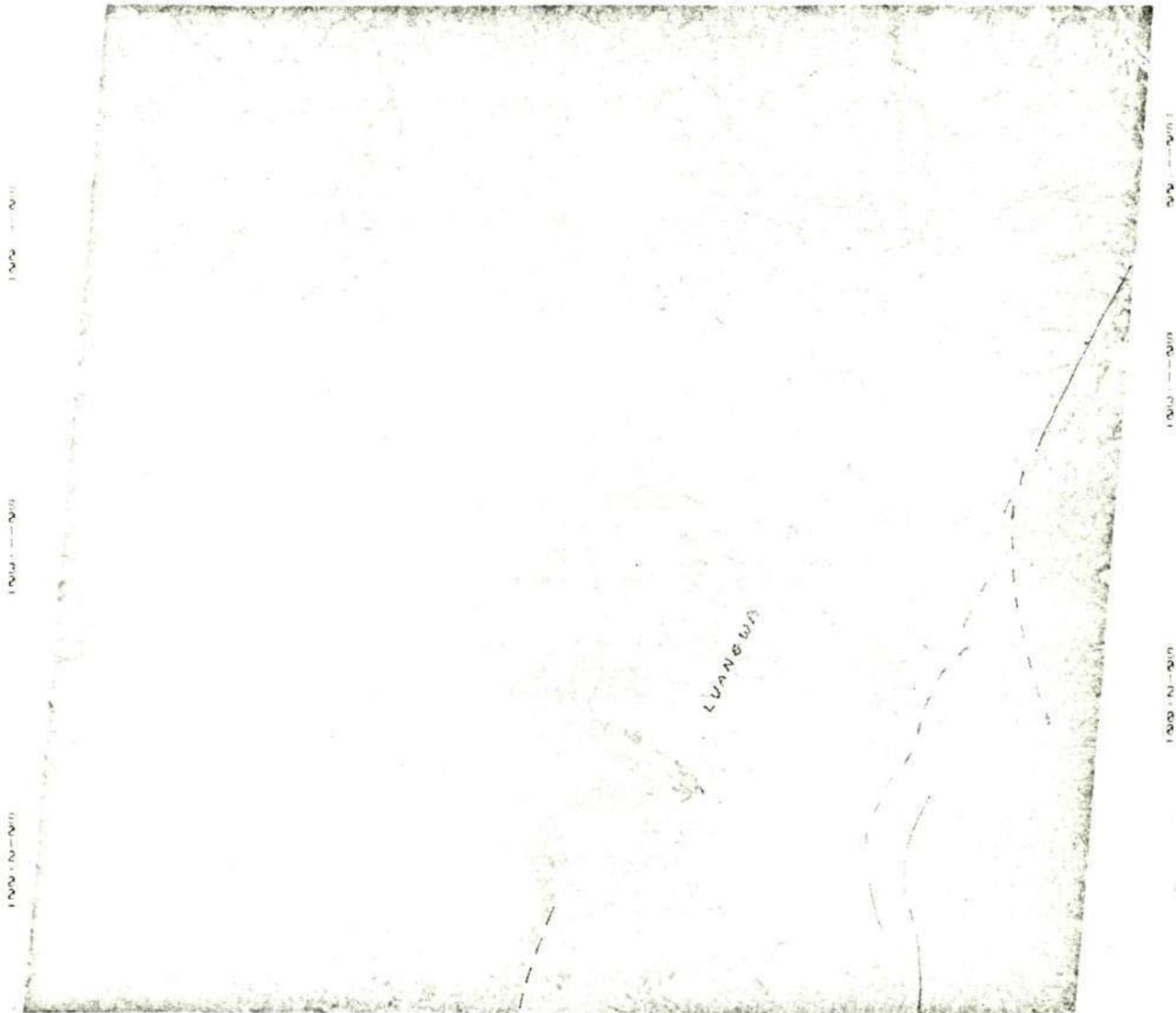
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Image 041. ERTS-1 image of northern Luangwa valley.

E032-02

E032-03

E032-04



28SEP72 C S11-30/E032-14 N S11-31/E032-21 MSS S R SUN EL55 AZ076 J08-0920-A-1 N-D-2L NASA ERTS E-1067-07260-S 01

Image 042. ERTS-1 image of central Luangwa valley.



Image 043. ERTS-1 image of southern Luangwa valley.

S015-001

E034-001

E034-301



E033-301 E034-001 E034-301
26SEP72 C S15-55/E034-03 N S15-56/E034-00 MSS 5 R SUN EL52 AZ070 100-0900-A-1-N-D-2L NASA ERTS E-1065-07155-5 01

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Image 058. ERTS-1 image of part of the lower Zambezi valley.

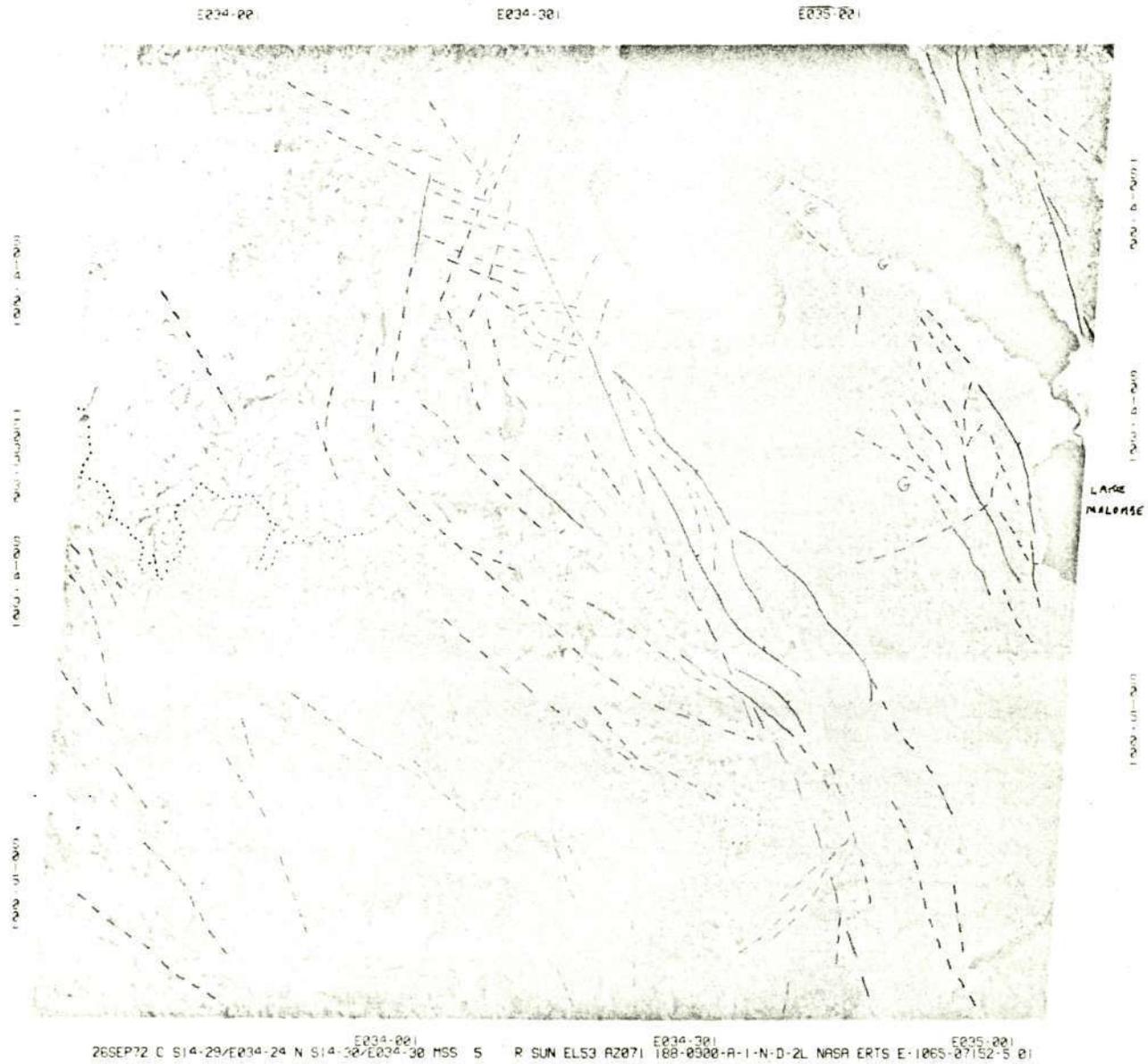


Image 057. ERTS-1 image of the region southwest of Lake Malawi and Lake Malombe, indicating end-Precambrian granites (G).

E034-001

E075-001

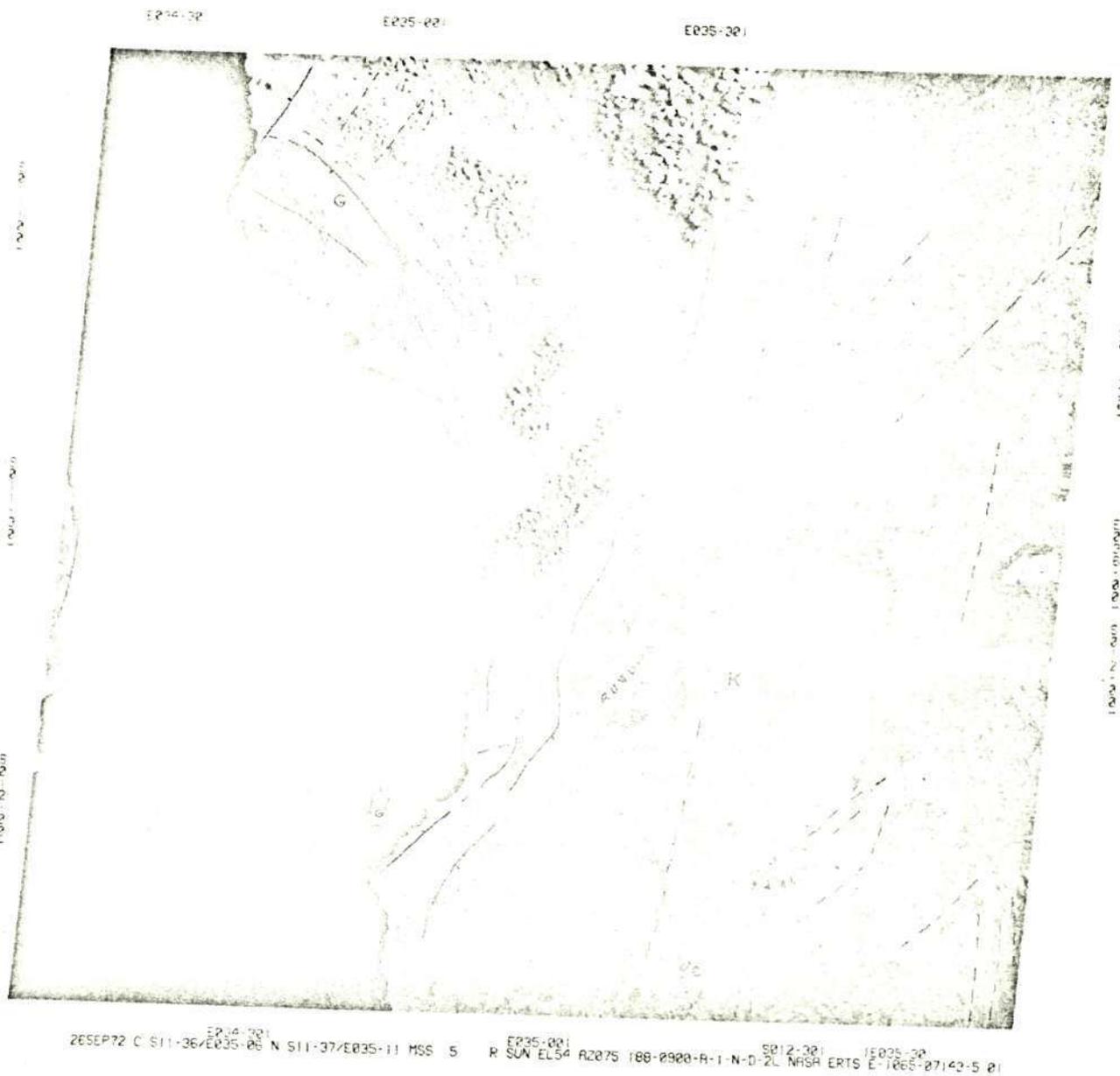
E035-001



E034-001 E075-001 E035-001
26SEP72 C S13-02/E034-45 N S13-04/E034-50 MSS 5 R SUN EL54 AZ073 100-0900-A-T-N-D-2L NASA ERTS E-1065-07150-5 01

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Image 056. ERTS-1 image of south-central Lake Malawi, indicating end-Precambrian granites (G).



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Image 055. ERTS-1 image of north-central Lake Malawi, indicating Mozambiquian metamorphics (PC), end-Precambrian granites (G), and Karroo sandstones (K).

The extensive work of the Geological Survey of Malawi, summarized in its 1966 Geological Map of Malawi, is generally confirmed from the ERTS imagery. However, the immediate bounds of the Lake Malawi rift include sectors in Mozambique and southernmost Tanzania, where its tectonics remain rather poorly known. The ERTS imagery therefore provides an ideal base for a unified structural geological map of this rift.

The western margin of the Lake Malawi rift, west of Lake Malombe, shows up clearly as a double escarpment (images 022 and 057). The continuation southward of this faulting into the north-northeast-trending Shire rift is not clear, however. [Note: The eastern margin of the Shire rift, curving south-southwestward from the eastern boundary faulting of Lake Malombe, lies just beyond the limits of the present ERTS imagery.] The easterly fault of the western-margin fault pair is made up of short arcuate sectors, convex toward the downthrown side. The westerly fault is quite linear, with a trend of 345° , and is more extensive than shown on the 1966 Geological Map of Malawi. It would be interesting to check if the easterly arcuate faults are near-surface vertical fractures extending up from an east-hading crustal fault plane expressed at the surface by the westerly trace.

The western-margin faulting, in this southern sector, terminates north in a northwest-trending zone of two perpendicular sets of fracturing, about latitude 14°S . Bloomfield (1970) notes that in this region the Dedza perthitic complex of the Mozambique Belt bears superimposed fold patterns: NW-SE (F1) regional isoclinal folding of the paragneisses, whose trend was reinforced by Mesozoic dike intrusions, and NE-SW (F2) broad, open folds. The ERTS imagery confirms that the denser lineation pattern is the NW-SE one (Bloomfield, 1970, Figure 3a). Precambrian lithological boundaries in this region, including that of the Dedza complex, are generally transitional and not sharply delineated on the ERTS imagery. An exception is the arcuate outcrop of calc-silicate granulites situated near $14^\circ 10'\text{S}$, $34^\circ 10'\text{E}$.

The uplifted hinterland, west of the western margin fault near latitude $14^\circ 30'\text{S}$, exposes two contrasting terrains on ERTS image 057. In the north, a lighter colored terrain with a NW-SE structural grain can be identified with the "Basement" gneisses

of the 1966 Geological Map of Malawi; to the south of what may be a vegetation-emphasized boundary lies darker, frequently more rugged terrain, to be identified with Proterozoic clastic sediments and a massive end-Precambrian granite pluton. The boundary between these two terrains may be determined by a NW-SE tectonism in the east and, farther west, may be related to similar boundaries exposed on ERTS images 018 and 019, obtained from the pass of 10 Sep. 72.

Late and post-orogenic (early Palaeozoic) granites of the Lake Malawi granitic province (Bloomfield, 1970) are identifiable on the ERTS imagery (marked "G"). These granites are often situated near or on the major Tertiary rift fault zones, although crucial sectors of this faulting are drowned under Lake Malawi.

The highlands extending northwestward from Lake Malombe show a north-northwest-trending lineation to the Mozambiquian gneisses. Plutons of various types, and strips of orthogneissic terrain, can be mapped from the ERTS imagery, but Mesozoic carbonatite vents and alkalic dikes (Woolley and Garson, 1970) cannot be discerned by the writer. Short fault traces of east-northeast trend may be an obscure expression of a hidden set of extensive crustal fractures of this trend.

Along the eastern margin of Lake Malawi, ground surveys have already shown the rift faulting to be more strongly developed than it is along the western margin. The ERTS imagery confirms this (image 056), although the arcuate pattern of the faulting is perhaps more complex than previously suspected. The dominant trend of N-S faulting appears to be following the Precambrian grain, between latitudes 12.5°S and 14°S east of the lake. Cross faults, on both sides of the lake, trend NW-SE (late Tertiary-Quaternary faults) and ENE-WSW (probably Precambrian lineations). A well-developed double-ring structure occurs at 13°30'S, 35°20'E.

The Likoma Island granite (latitude 12°00'S) is considered by Bloomfield (1966, 1970) to be situated on a narrow east-northeast-trending shear zone, extending from Zambia across Lake Malawi into Mozambique. ERTS image 055 (and 020) covers only the eastern side of the lake at this latitude, but there it is difficult to identify any east-northeast lineations except possibly close to the shore. However, the masking effect of the Ruvuma valley Karroo sequence must be considered, if the shearing was not reactivated in the Cainozoic.

The Ruvuma valley declines northeastward away from the east side of Lake Malawi at latitude 12°S. For the first 60 km, it is separated from the lake by a narrow sinuous horst, reminiscent of the Kiyimbi horst, west of Lake Tanganyika (see Section 3.3). The denuded aspect of this horst may testify to a Mesozoic initiation of the faulting (Dixey, 1956). The horst widens into a highland block to the north, where the structural trend of the Mozambique Belt metamorphics curves from north to northwest in a great arc, and thus turns away from the northeast trend of the Ruvuma trough.

The lake shore follows the Mozambiquian trend, but has an accentuated curve due to the headland protruberance of the Liuli granitic massif, at latitude 11°00'S. The rift faulting runs close to the granite-metamorphics boundary and appears to be terminated by a NE-SW cross fault at the northern end of the granite (also at the northerly limit of image 055).

The NE-NNE trending trough of the Ruvuma valley cuts across the Precambrian grain. It is interesting that the rift faulting has preferred to follow the earlier of these two structures here. The thick, undeformed sedimentary sequence of the Karroo (Haughton, 1963) shows weakly some northeast and north-northeast lineations, reflecting a Karroo tectonism that probably extended to the Rufiji valley and the Tanzanian coast, near Dar-es-Salaam. This will be sought on future ERTS imagery.

3.5 Other Regions

Single ERTS images cover some other regions of special interest. Selected here are the Aswa mylonite zone, at the northern end of the Western Rift, and part of Afar, Ethiopia. It is of Ethiopia that the writer has some ground experience, but thus far, very little cloud-free ERTS imagery of this country is available.

3.5.1 Aswa mylonite zone

The ERTS pass of 13 Sep. 72 traversed the northern sector of the Western Rift. Cloud cover hampers interpretation of the structures of the Lake Albert rift, but the Aswa mylonite zone shows up clearly and sharply on image 176. This zone is generally

recognized to cut abruptly across and to terminate the NE-SW faulting of the Western Rift, north of Lake Albert (Whiteman, 1965). Cloud cover on the ERTS imagery is too great to investigate whether or not there is any NE-SW faulting continuing across the unexplored country to the north of the Aswa mylonite zone, but the zone itself can be described here.

The White Nile at latitude 3.5°N , following a course of about 070° parallel to the "final" rift faulting, abruptly turns at Nimule to 315° . This is the trend of the Aswa mylonite zone, which extends northwest from Nimule for at least 200 km. Whiteman (1971) has summarized what little is known about this zone in Sudan from reconnaissance ground traverses. Its southeasterly extension into Uganda has been studied by Almond (1969), who considers that the zone extends under Mt. Elgon to continue as the Nandi fault (see Section 3.2). If this is the case, this is a fundamental late-Precambrian lineament at least 700 km long.

ERTS image 176 shows the Aswa mylonite zone in Sudan to be a severe fracture zone with a flattened S-shaped plan. The fracturing is splayed clockwise in both directions from a nexus at $4^{\circ}20'\text{N}$, $31^{\circ}25'\text{E}$. This fits with Almond's (1969) proposal for sinistral shear along the Aswa zone in Uganda. Young volcanic cones on the northern fringe of the western arm of the zone reveal a previously unreported Quaternary volcanic activity, consonant with recent seismicity in this region (Almond, 1969; Mohr, 1969).

Two ring structures, 6 to 8 km in diameter, occur north of Nimule.

3.5.2 Afar, Ethiopia

The only window to date (October 1972) in the "kremt" cloud cover of Ethiopia is over part of southern Afar. Afar is a triple-rift junction, and its structures are complex and controverted (Tazieff, Varet, Barberi, and Giglia, 1972; Mohr, 1967a, 1970, 1972).

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0201-001 11023-32 0201-001 0202-001
13SEP72 C N04-17/E031-37 N N04-15/E031-41 MSS 5 R SUN EL57 A2089 188-0719-G-1-N-D-2L NASA ERTS E-1052-07304-5 01

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Image 176. ERTS-1 image of the Aswa mylonite zone, west of Nimule, on the Sudan-Uganda border.

Image 136, from the pass of 7 Sep. 72, confirms the existence of the fault belts mapped previously (Mohr, 1967a, 1970, 1972; Taieb, Coppens, Johanson, and Kalb, 1972). As expected, however, the ERTS imagery provides a much better basis for unified regional mapping of the more important structures. For example, despite poor contrast, image 176 reveals the arcuate faulting extending northwest from Langudi volcano ($10^{\circ}35'N$, $41^{\circ}00'E$), the parallel existence of the Issa graben (Taieb *et al.*, 1972) and a fault belt 40 km farther east (Mohr, 1967a, 1972), and the existence of important NE-SW fractures in the Aisha horst, south of the Gulf of Tajura (see also ERTS image 172, 24 Sep. 72). These last are notably parallel to a proposed transform fault in the Gulf of Tajura (Roberts and Whitmarsh, 1969), and suggest that this region may be of transitional oceanic-continental character.

All rules exist to be broken. The writer's resolve not to discuss any imagery received after the end of October was dissolved with the arrival on 10 November of two superb images of Afar. Image 157 of the pass of 13 Oct. 72 covers the eastern corner of Afar and the southern half of the Danakil horst. Image 158 covers the Lake Abbe-Gulf of Tajura region, immediately to the south.

Images 157 and 158 are of extraordinary clarity, and show in fine detail the almost catastrophic structural deformation of this awesome, slightly eerie global tectonic nexus. The results of ground-based geological surveys of Afar have been discussed by Tazieff *et al.* (1972) and Mohr (1967a, 1971b, 1972). Essentially, the late Tertiary Afar Series flood basalt-mugearite sequence forms a visible basement that has been intensely sliced by a complex mesh of Lower-Middle Quaternary fault belts. Late Quaternary faulting has rejuvenated some of these belts, but without drastically modifying some extensive Middle-late Quaternary sedimentary basins (Taieb *et al.*, 1972). These basins show up light on the ERTS imagery, especially the saline deposits of the Lake Assal and Dobi graben.

Detailed mapping of Afar from ERTS imagery is the province of Dr. P. Kronberg (Clausthal), but points of interest in relation to the writer's earlier work can be briefly mentioned.



EP41-20 EP41-30 EP42-20
 27SEP72 C N12-21/E241-33 N N29-59/E241-37 H55 5 P SUN ELS7 R2294 188-2635-N-1-N-D-2L NASA ERTS E-1246-07223-5 B1

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Image 136. ERTS-1 image of southern Afar, with fault belts partially revealed through cloud cover.

E042-201

E042-30

E043-001



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Image 157. ERTS-1 image of eastern Afar and southern Danakil horst, showing meridional alignment of volcanic centers along the western edge of the image and complex fantail fault belts in the south.

E041-301

E042-001

E042-301



130CT72 C N11-34/E041-55 N N11-30/E041-59 MSS 5 R SUN EL55 AZ122 189-1137-R-1-N-D-2L NASA ERTS E-1082-07022-5 01

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Image 158. ERTS-1 image of Lake Abbe and Gulf of Tajura region of Afar, showing fantail faulting in the north; the interrelationships of the Gawa, Gumá, and Dobi graben, again in the north; the Damahali volcanic shield immediately west of Lake Abbe; the Wonji fault belt and fresh graben south of Gabillemma volcano, near the southwest corner of the image; and Tendahó cotton plantation on the western edge, near the center of the image.

The Dubbi volcanic alignment (Mohr, 1967a), traversing the central Danakil horst in a NNE-SSW direction, is clearly apparent on image 157, yet no large crustal displacements of this trend are in evidence on the surface to link the centers. A fundamental lineament is presumably buried beneath the young lavas and tuffs of the region, and poses a caution on the relating of surficial and transcrustal fractures.

A huge fantail of fine, crustal fracturing extends northwestward from Gubet Kharab, via Lake Assal. The remarkable, sinuous Gawá graben is part of this fantail, but the arcuate Gumá graben (Mohr, 1971b) is a separate, major entity, which may be a surface expression of a crustal nucleus responsible for the form of the fantail. Another hypothesis has been put forward by Mohr (1968), in terms of an arcuate stress pattern.

The southeast-trending fault belts of northern and western Afar project across to the Lake Abbe region, but ERTS image 158 suggests that a major curvilinear adjustment, southward to a south-southwest-trending (Wonji fault belt) direction, occurs immediately west of Lake Abbe. Damahali volcano is situated on this curving, linking fault belt. West of this newly recognized belt, the faults are more locally irregular in pattern, though just as dense, compared with the majestic sweep of faults to the east. This suggests a regional pattern of stress accumulation to the east, in possibly thinner crust, compared with local resistances to such a pattern, in possibly thicker crust, to the west.

The boundary between the NW-SE fault belts north and northeast of Lake Abbe and the E-W fault belts south and southeast of the lake (Mohr, 1967a) appears from ERTS image 158 to be an east-northeast-trending linear fracture zone. Though outside the region mapped by Mohr (1967a), this zone must be considered a candidate for a "cross-rift lineament," subject to ground confirmation of its existence. Smaller such lineaments are expressed at latitude $11^{\circ}35'N$ at the western edge of image 158, crossing the western end of the Gawa graben, but conclusive evidence for the hotly controverted existence of cross-rift lineaments must await good imagery of southwestern Afar, close to the main Ethiopian rift.

The form of the Aisha horst is more complex than had previously been realized. Its southern sector may indeed be merely a northward protruberance from the Somalian plateau, and other exposures of ancient, continental-type rocks may be "islands" in quasi-oceanic crust. This question remains open, but revisions to the plate-tectonic scheme of Mohr (1972) are already indicated and further emphasize the value of the ERTS imagery to structural geology and plate tectonics.

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Before joining Smithsonian Astrophysical Observatory in 1967, he spent 10 years at Haile Selassie I University (formerly University College, Addis Ababa), with intervening 1-year research fellowships at Sheffield University and Cambridge University.

Since joining the Smithsonian Astrophysical Observatory, he has retained his interest in Ethiopian rift valley studies: in particular, in the relationships between tectonism and volcanism, and in establishing precise geodetic nets to detect crustal deformation in the rift.